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Bounds on the Higgs Boson Mass from M_W*

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Abstract

Recent experimental and theoretical progress in the M_H estimates from M_W and $\sin^2\theta_{eff}^{lept}$ is reviewed, with particular emphasis on the role played by M_t. Assuming that the SM is correct and taking into account the lower bound on M_H from direct searches, we derive restrictive bounds on M_W and M_t. We also discuss a representative "benchmark" scenario for the possible future evolution of these parameters. Amusingly, this benchmark scenario suggested some time ago a value for M_t that turned out to be in very close agreement with its most recent experimental determination.

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1 Introduction

The Standard Model of Particle Physics (SM) has been very successful in describing the interactions among elementary particles involving the fundamental forces, with the exception of gravity. Although at present no experimental data are in sharp contradiction with the predictions of this theory, many questions remain open. In particular, one important component of the theory, the Higgs boson, responsible via the Higgs mechanism for the generation of the masses of all fundamental particles, has yet to be discovered.

The precise electroweak experiments performed at the colliders (LEP, SLD, C0, CDF) can be used to check the validity of the Standard Model and, within its framework, to get important informations about its parameters. The high accuracy of the measurements makes their interpretation sensitive to quantities that appear in the electroweak corrections, such as the mass of the top quark M_t and the mass of the Higgs boson M_H. The leading dependence of the electroweak corrections on M_t and M_H is quadratic and logarithmic, respectively; as a consequence, it is more difficult to put sharp constraints on M_H that on M_t. In the case of the top quark, the analysis of the Z^0-resonance observables led to a rather precise prediction of M_t, before its experimental discovery. This indirect prediction turned out to be in good agreement with the value of M_t measured at Fermilab in 1995, giving strong evidence for the presence of electroweak corrections. Although it is still interesting and important to derive indirect predictions for the masses of already discovered particles, such as M_W and M_t, at present the main focus of the indirect analysis is on the determination of the allowed ranges for the great missing piece, the mass of the Higgs boson.

The EWWG (LEP Electroweak Working Group) performs a wide set of χ^2-minimization fits to compare all the available experimental data with the theoretical predictions of the SM [1]. This procedure, known as a global analysis, provides important information, tests the validity of the theory, and attempts to find deviations that may signal the presence of new physics beyond the SM [2]. On the other hand, it has been argued that, aside from the global analyses, it is also important to confront the theory separately with the precise observables that are most sensitive to M_H, such as M_W and $\sin^2\theta_{eff}^{lept}$ [3, 4, 5]. In fact, it is in principle possible that striking discrepancies between crucial observables and important information may be blurred in the global analysis [6].

In the following, we will first discuss the bounds on M_H that can be ob-

tained solely from the experimental value of M_W, giving particular attention to the role played in this analysis by M_t. In this context we will also review the main sources of theoretical uncertainty. We will then comment briefly on the bounds that can be obtained using the experimental value of $\sin^2\theta_{eff}^{lept}$ and the unresolved issues involving the current measurements of this important parameter. We will finally present a different analysis in which, assuming that the SM is correct and taking into account the lower limit on M_H from direct searches, we derive restrictive bounds on M_W, M_t. Analogous bounds for $\sin^2\theta_{eff}^{lept}$ have been obtained [7].

2 Bounds on the Higgs Boson Mass from M_W

There are several factors that single out the M_W determination as particularly important:

- The LEP2 and Tevatron experimental measurements of M_W are in excellent agreement;
- As we will show in this Section, it places sharp restrictions on M_H;
- The relevant electroweak correction Δr [8] has been now fully evaluated at the two-loop level [9].

In other words, in the M_W case, we compare very precise theoretical results with highly consistent experimental data. This is particularly important given the extreme sensitivity of these tests. Since the leading dependence of the theoretical formula for M_W is logarithmic in M_H, small shifts in the experimental values lead to large changes in M_H. As we mentioned before, this is one of the reasons that complicates the indirect determination of M_H (in contrast, for example, to the analogous determination of M_t).

The recent experimental value for M_W, derived from the combination of the LEP2 and Tevatron results, is

$$(M_W)_{exp} = 80.426 \pm 0.034\,\mathrm{GeV}\,. \tag{1}$$

We will perform the fits using the theoretical formula introduced in Ref. [10], in the effective scheme of renormalization (EFF) [11]. The results will be checked using also the more complete formula by Awramik *et al.* [12] that takes into account the complete two-loop contributions to Δr.

In order to stress the importance of M_t, we first perform the analysis using the Winter 2003 value of this parameter, i.e. $M_t = 174.3 \pm 5.1$ GeV, together with $\Delta\alpha_h^{(5)} = 0.02761 \pm 0.00036$ and $\alpha_s(M_Z) = 0.118 \pm 0.002$. Using the formula of Ref. [10], we obtain

$$M_H = 45^{+69}_{-36}\,\mathrm{GeV}\,; \quad M_H^{95} = 184\,\mathrm{GeV}\,, \tag{2}$$

while employing the expressions of Ref. [12], we have

$$M_H = 36^{+65}_{-33}\,\mathrm{GeV}\,; \quad M_H^{95} = 168\,\mathrm{GeV}\,. \tag{3}$$

These results seem to suggest a very light Higgs boson. In fact, the central values in the predictions of Eqs. (2) and (3) are well below the 95% C.L. lower bound $(M_H)_{L.B.} = 114.4\,\mathrm{GeV}$ from direct searches. On the other hand, the 95% C.L. upper bound M_H^{95} in Eqs. (2, 3) are still well above $(M_H)_{L.B.}$. Thus, solely from this analysis we cannot conclude that there is clear evidence for inconsistencies and, consequently, need for "new physics". It is interesting to compare the situation depicted in (2) and (3) with the corresponding analysis performed with the data available in Winter 2002: using $(M_W)_{exp} = 80.451 \pm 0.033$ GeV (the experimental value for M_W in Winter 2002), we obtain in the EFF scheme [10]

$$M_H = 23^{+49}_{-23}\,\mathrm{GeV}\,; \quad M_H^{95} = 122\,\mathrm{GeV}\,, \tag{4}$$

a very worrisome low value! It is noteworthy to observe how a change in the central value of $(M_W)_{exp}$ of less then 1 σ, without changes in its error bar, has significantly improved the consistency with the theory.

Before commenting on the effect of M_t, we briefly review the sources of uncertainty in the theoretical calculation of M_W. There are two types of theoretical errors, one due to the truncation of the perturbative expansion (*truncation error*) and one due to the uncertainties in the input parameters employed in the calculation (*parametric error*). Including the effect of QCD corrections, the truncation error in the calculation of M_W has been estimated to be $\approx 7\,\mathrm{MeV}$ in Ref. [10] and $\approx 4\,\mathrm{MeV}$ in Ref. [12]. A parametric error of approximately the same size can be obtained by shifting $\Delta\alpha_h^{(5)}$ by about 1 σ or M_t by only 1 GeV. We can therefore conclude that the main source of theoretical error is still related to the uncertainty in the measurement of M_t! A summary of the theoretical errors in the calculations of M_W and $\sin^2\theta_{eff}^{lept}$ is given in Table 1.

Table 1: Parametric error in the calculation of s^2_{eff} and M_W to be compared with a truncation error of 6×10^{-5} in s^2_{eff} and 7 MeV (4 MeV) in M_W.

Parameter	1σ shift	Δs^2_{eff}	ΔM_W
$\Delta\alpha_h^{(5)}$	0.00036	1.3×10^{-4}	6 MeV
M_t	4.3 GeV	1.4×10^{-4}	26 MeV

After a glimpse at Table 1, it is not surprising that the new experimental value $M_t = 178.0 \pm 4.3$ GeV, has a big effect on the theoretical prediction of M_W and therefore on the estimate of M_H. Repeating the analysis of Eqs. (2) and (3) with the new value for M_t, we obtain

$$M_H = 74^{+83}_{-47}\,\text{GeV}\,; \quad M_H^{95} = 238\,\text{GeV} \tag{5}$$

and

$$M_H = 62^{+78}_{-43}\,\text{GeV}\,; \quad M_H^{95} = 216\,\text{GeV}\,, \tag{6}$$

respectively, a significantly less restrictive range for M_H. The effect of the change in M_t is depicted in Fig. 1, employing the theoretical expression of Ref. [10] in the effective scheme of renormalization.

It will be very important to see in which direction the experimental values of M_W and M_t evolve in future, more accurate, experiments. Some plausible future scenarios are described in Section 4.

3 The $\sin^2\theta^{lept}_{eff}$ Anomaly

The analysis based on $\sin^2\theta^{lept}_{eff}$ is more complicated. Averaging all the different measurements, one obtains $(\sin^2\theta^{lept}_{eff})_{exp} = 0.23150 \pm 0.00016$ [1] with a $\chi^2/\text{Dof} = 10.5/5$ corresponding to a confidence level of 6.2%. The averages derived from the leptonic and hadronic observables are $(\sin^2\theta^{lept}_{eff})_{(l)} = 0.23113 \pm 0.00021$ and $(\sin^2\theta^{lept}_{eff})_{(h)} = 0.23214 \pm 0.00027$, respectively, a difference of almost 3 σ! Thus, at present, the results obtained from the leptonic and hadronic sectors are not in good agreement.

On the theoretical side, a complete two-loop calculation for the prediction of s^2_{eff} is not yet available. Our analysis employs the theoretical formula of

Ref. [10] in the effective scheme of renormalization. In turn, this expression is based on the calculation reported in Ref. [11] and includes two-loop effects enhanced by powers of M_t^2/M_W^2, as well as QCD corrections.

Using the world average $(\sin^2\theta_{eff}^{lept})_{exp} = 0.23150 \pm 0.00016$, together with the "new" value $M_t = 178.0 \pm 4.3$ GeV, we find

$$M_H = 159^{+92}_{-61}\,\mathrm{GeV}\,; \quad M_H^{95} = 332\,\mathrm{GeV}\,. \tag{7}$$

This result is in good agreement with the SM, in the sense that it suggests a light Higgs boson with a mass above the region excluded by direct searches. However one should not forget that the poor agreement between the leptonic and hadronic determinations of $\sin^2\theta_{eff}^{lept}$ is hidden in the average.
If we simply use the data from hadronic asymmetries, we obtain instead

$$M_H = 491^{+342}_{-210}\,\mathrm{GeV}\,; \quad M_H^{95} = 1150\,\mathrm{GeV}\,, \tag{8}$$

a significantly heavier Higgs boson. Finally using $(\sin^2\theta_{eff}^{lept})_{(l)} = 0.23113 \pm 0.00021$ from leptonic asymmetries, we find

$$M_H = 76^{+58}_{-35}\,\mathrm{GeV}\,; \quad M_H^{95} = 190\,\mathrm{GeV}\,, \tag{9}$$

a result that is in very good agreement with that reported in Eq. (5) on the basis of the M_W input.

We see that hadronic asymmetries prefer a medium-heavy Higgs boson, while leptonic asymmetries, together with M_W, suggest a light particle. The situation is depicted in Fig. 2.

If we want to explain this contradiction, there are two possibilities[1]:

- The differences are due to statistical fluctuations, maybe enhanced by unknown systematics.
- The hadronic data is not described correctly by the SM.

The second possibility requires the introduction of some "new physics" in the hadronic sector. If the fluctuations were to settle on the side of the leptonic averages, the first possibility may also require new physics, since the

[1] This is known in the literature as the "Chanowitz argument" [13], and has been used in the past to stress the necessity of "new physics" beyond the SM. In the light of the new value for the top quark mass, of course, this argument is losing some of its original strength.

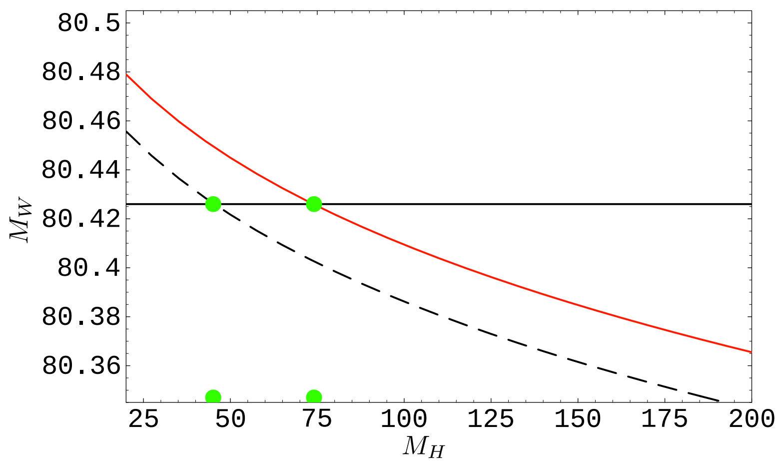

Figure 1: The theoretical prediction for M_W obtained with the new value of M_t (full red line) is approximately 20 MeV higher then the one obtained with the old M_t value (dashed black line), leading to an increase in the indirect determination of M_H (green dots).

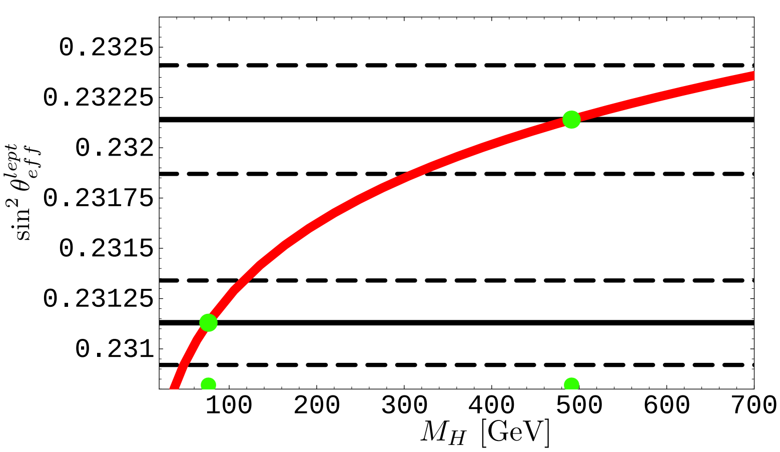

Figure 2: Comparison of the theoretical prediction for s^2_{eff} with the experimental averages derived from the leptonic observables ($s^2_{eff} = 0.23113 \pm 0.00021$) and hadronic observables ($s^2_{eff} = 0.23214 \pm 0.00027$). The two values lead to very different determinations of M_H (green dots).

predicted M_H is smaller than $(M_H)_{L.B.}$. This will certainly be the case if in future experiments the central values remain as they are and the error bars are significantly reduced.

As a final application, we combine the analysis based on M_W and $\sin^2\theta_{eff}^{lept}$, using the most recent M_t value. If the world average $\sin^2\theta_{eff}^{lept} = 0.23150 \pm 0.00016$ is employed, we obtain

$$M_H = 138^{+80}_{-51}\,\mathrm{GeV}\,; \quad M_H^{95} = 280\,\mathrm{GeV}\,. \tag{10}$$

Instead, if we restrict ourselves to the value $(\sin^2\theta_{eff}^{lept})_{(l)} = 0.23113 \pm 0.00021$ derived from the leptonic observables, we have

$$M_H = 75^{+54}_{-33}\,\mathrm{GeV}\,; \quad M_H^{95} = 177\,\mathrm{GeV}\,. \tag{11}$$

4 Bounds on M_W and M_t. A Benchmark Scenario

Assuming that the Standard Model is correct and taking into account the lower bound on M_H from direct searches, we discuss bounds on M_W and M_t at various confidence levels. This permits to identify theoretically favored ranges for these important parameters in the Standard Model framework, regardless of other observables. This section is based on the work of Ref. [7], in which a similar analysis based on s^2_{eff} and M_t was also performed.

Let us first consider the data in Winter 2003 and $\Delta\alpha_h^{(5)} = 0.02761 \pm 0.00036$. Fig. 3 shows the theoretical SM curve $M_W(M_H, M_t)$ for $M_H = 114.4$ (dashed line) evaluated with the simple formulae of Ref. [10] in the effective scheme of renormalization [11], as well as the 68%, 80%, 90%, 95% C.L. contours derived from the experimental values $(M_W)_{exp} = 80.426 \pm 0.034\,\mathrm{GeV}$, $(M_t)_{exp} = 174.3 \pm 5.1\,\mathrm{GeV}$ (Winter 2003).

To simplify the analysis we take the restriction $M_H \geq 114.4\,\mathrm{GeV}$ to be a sharp cutoff rather than a 95% C.L. bound. At a given C.L. the allowed region lies within the corresponding ellipse and below the $M_H = 114.4\,\mathrm{GeV}$ SM theoretical curve (dashed line), which we call the boundary curve (B.C.). It turns out that, to a good approximation, the maximum and minimum M_W and M_t values in a given allowed region are determined by the intersections of the B.C. with the associated ellipse. The allowed M_W and M_t ranges determined by such intersections are shown in Table 2 for the 80%, 90%,

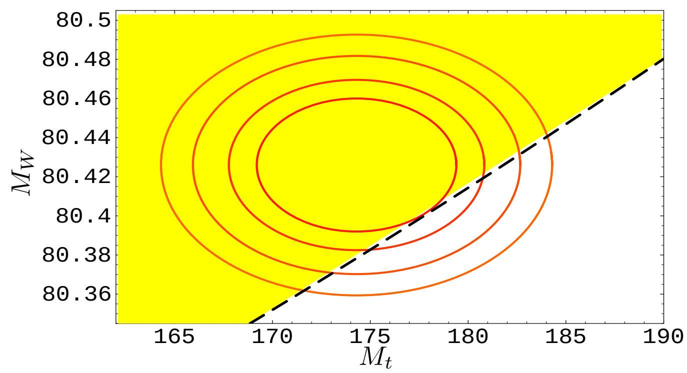

Figure 3: Theoretical SM curve $M_W(M_H, M_t)$ for $M_H = 114.4$ (dashed line) together with 68%, 80%, 90%, 95% C.L. contours derived from $(M_W)_{exp}$ and $(M_t)_{exp}$ (Winter 2003).

95% C.L. domains. As M_H increases beyond 114.4 GeV, the allowed ranges decrease in size. Clearly they are considerably more restrictive than the corresponding intervals derived from current experimental errors.

Table 2: Allowed ranges for M_W and M_t. Results obtained in the EFF scheme with $\Delta\alpha_h^{(5)} = 0.02761$ and $(M_t)_{exp} = 174.3 \pm 5.1$ GeV (Winter 2003).

EFF / $\Delta\alpha_h^{(5)} = 0.02761$	range M_W [GeV]	range M_t [GeV]
80% C.L.	80.401 ± 0.018	177.9 ± 2.9
90% C.L.	80.401 ± 0.030	177.9 ± 4.8
95% C.L.	80.401 ± 0.040	177.9 ± 6.3

The mid-points $(80.401, 177.9)$GeV of the allowed regions in Table 2 are independent of the C.L. and are shifted from the experimental central values by less then 1 σ. This makes them particularly attractive representative points, which we identify as benchmarks to illustrate the possible future evolution of these fundamental parameters.

This analysis was first performed in Winter of 2003. It is amusing to observe how the benchmark point for M_t turned out to be very close to its new experimental central value.

As a last application, we repeat the same analysis using the new value for M_t (Fig. 4 and Table 3).

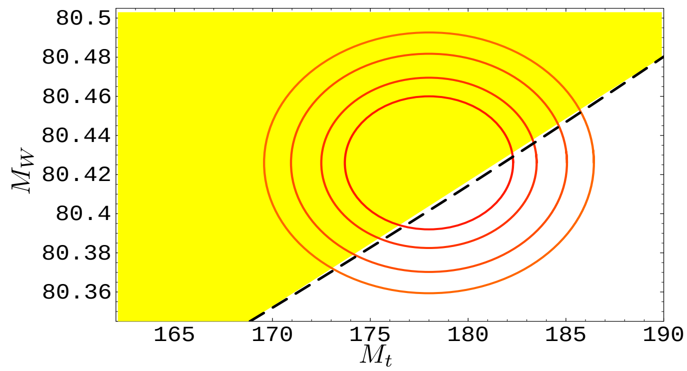

Figure 4: Same as Fig. 3, using the new experimental data (April 2004).

Table 3: Allowed ranges for M_W and M_t. Results obtained in the EFF scheme with $\Delta\alpha_h^{(5)} = 0.02761$ and $(M_t)_{exp} = 178.0 \pm 4.3\,\text{GeV}$ (April 2004).

EFF / $\Delta\alpha_h^{(5)} = 0.02761$	range M_W [GeV]	range M_t [GeV]
68% C.L.	80.412 ± 0.018	179.5 ± 2.8
80% C.L.	80.412 ± 0.025	179.5 ± 3.9
90% C.L.	80.412 ± 0.034	179.5 ± 5.2
95% C.L.	80.412 ± 0.041	179.5 ± 6.3

Thus, the benchmark scenario currently prefers a further increase of $\approx 1.5\,\text{GeV}$ in M_t and a value for M_W that coincides with the most precise present measurement, namely the LEP2 central value $M_W = 80.412\,\text{GeV}$.

5 Conclusions

At present, there is no compelling evidence of new physics beyond the SM. The new experimental value of M_t has significantly improved the agreement between the SM and the experimental data and, in particular, the estimate

of M_H obtained via M_W. However, the central value of this predictions is still smaller than $(M_H)_{L.B.}$ by $\approx 40-50\,\mathrm{GeV}$. We emphasize that the M_H analysis is very sensitive to M_W and M_t. Thus, it will be very important to see how their values evolve in the future, as the experimental accuracy increases. In this connection, assuming that the SM is correct, we have derived bounds on M_W and M_t that are considerably more restrictive than the corresponding intervals derived from current experimental errors. We have also discussed a representative "benchmark" scenario for the possible future evolution of these parameters. Amusingly, this analysis suggested a value for M_t that turned out to be in very close agreement with its most recent experimental determination.

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